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The impact of improved wood-burning stoves on fine particulate matter concentrations in rural Mexican homes

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To evaluate the impact of improved wood burning stoves on indoor air pollution, 53 homes in a rural town in Michoacán, Mexico, were selected from a health intervention study and monitored before and after receiving improved wood-burning stoves. Fine particulate matter — particles with aerodynamic diameter less than 2.5 μm ($PM_{2.5}$) — concentrations were measured in the central plaza of the community and in three microenvironments in the home (next to the stove, in the kitchen away from the stove, and outdoor patio). Forty-eight hour mean $PM_{2.5}$ concentrations in homes that burned wood in open fires were 693 $\mu g/m^3$ (95% CI: 246–1338) near the stove, 658 $\mu g/m^3$ (95% CI: 67–1448) in the kitchen away from the stove, and 94 $\mu g/m^3$ (95% CI: 36–236) on the patio. Mean ambient 24-h concentrations in the main plaza of the community were 59 $\mu g/m^3$ (95% CI: 29–92). Paired measurements before and after the installation of the *Patsari* improved wood-burning stove indicate a median 71% reduction in $PM_{2.5}$ concentrations near the stove and 58% reductions in kitchen concentrations, whereas patio and main plaza concentrations remain unaffected. Only 44% of participants reported to use their *Patsari* stoves exclusively during the transition period. Even with the predominant mixed use of the *Patsari* stove with open fires, estimated daily average personal exposures to $PM_{2.5}$ were reduced by 50%.
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Introduction

Evidence from both urban and rural air pollution studies has demonstrated that exposure to particulate matter is associated with increased risk of mortality and morbidity outcomes (Dockery et al., 1993; Bruce et al., 2000; Pope et al., 2002; Dominici et al., 2003). One of the largest sources of exposure to particulate matter in rural environments of the developing world is the burning of biomass for home energy needs, such as heating or cooking. Air pollution levels in homes where biomass is burnt for household energy needs have been found to be up to 50 times greater than the US National Ambient Air Quality Standards (NAAQS) for outdoor 24-h levels set at 65 μg/m^3 (USEPA, 2002; von Schirnding et al., 2002; Saksena et al., 2003). Exposures to indoor air pollutants originating from the burning of solid fuels depend on a number of factors, including fuel type and quality, housing characteristics, cooking and heating methods, time–activity patterns, and season (Saksena et al., 1992). These factors lead to wide variability of pollution levels between different homes and communities (Saksena et al., 2003). Studies have also found that pollution within the same home can be highly variable between different days of the week (He et al., 2005) and even within the same day (Ezzati et al., 2000a, b) depending on cooking activities.

Exposure to biomass smoke has been associated with increased risk of acute lower respiratory infections in children and chronic obstructive lung disease in adults (Bruce et al., 2000). Also, emerging evidence suggests an association with tuberculosis, adverse pregnancy outcomes, asthma, otitis media, cancer of the upper airways, and cataracts (Bruce et al., 2000; Smith et al., 2004). Smith et al. (2004) found that worldwide 1.6 million deaths and 38.5 million disability adjusted life years are attributed to indoor smoke

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from solid fuels, accounting for 3% of the global burden of disease.

Approximately 25% of Mexican homes use wood as their main energy source, either exclusively or in combination with LPG stoves (Díaz and Masera, 2003). These homes are mostly located in rural, indigenous communities. Indoor air pollution studies in several of these communities have encountered elevated levels of particulate matter in the kitchens of homes using biomass fuels (Brauer et al., 1996; Saatkamp et al., 2000; Riojas-Rodriguez et al., 2001). For instance, in the state of Chiapas, 16-h averaged PM_{10} concentrations reached 286 and 589 $\mu g/m^3$ for dry and wet seasons, respectively (Riojas-Rodriguez et al., 2001); in the state of Mexico, 9-h averaged $PM_{2.5}$ concentrations reached 555 $\mu g/m^3$ (Brauer et al., 1996), and in the state of Michoacán, PM_7 concentrations ranged between 655 and 995 $\mu g/m^3$ during the cooking period (Saatkamp et al., 2000).

A number of efforts have been made by Mexican NGOs, government, and academia to address this issue by disseminating improved wood-burning stoves to rural homes with a wide range of outcomes (Masera et al., 2005). Few systematic evaluations have been made on the effectiveness of improved stove programs in reducing indoor air pollution (McCracken and Smith, 1998; Ezzati et al., 2000a; Naeher et al., 2000; Albalak et al., 2001; Bruce et al., 2004). A recent interdisciplinary effort has begun in Mexico to disseminate 1500 improved *Patsari* wood-burning stoves in the state of Michoacán and to comprehensively evaluate their social, health, and environmental impacts (Masera et al., 2005). The air pollution component of this program has included integrated sampling of particulate matter in home and outdoor microenvironments as well as continuous measurements of particulate matter and carbon monoxide both in the home as well as personal sampling (GIRA, 2005). This paper describes the integrated sampling of particulate matter in indoor and outdoor microenvironments using gravimetric methods as well as the estimation of daily average personal exposures to evaluate the air pollution benefits of this improved stove program.

Methods

Study Site and Population

The study took place in the town of Comachuén, an indigenous Purépecha community of approximately 4300 people located in the state of Michoacán in central western Mexico. Over 95% of homes in Comachuén burn wood in open fires for their household energy needs (INEGI 2001), such as cooking meals, preparing tortillas and nixtamal (the corn base for tortillas), and heating water for bathing. The town of Comachuén is located in the Sierra Purépecha, at an altitude of 2600 m above sea level and surrounded by hills. Its geographical location results in frequent thermal inversions in the morning hours, trapping in wood smoke as seen in Figure 1.

Characteristics of Study Homes

Typical homes in Comachuén consist of several separate room structures built around a common patio (Figure 2). Bedroom floors are constructed from concrete (47%), dirt (36%), or wood (14%), and walls are made of either wood (50%) or brick (50%). Kitchens in Comachuén are mostly made with wooden walls (90%) and dirt floors (67%). In over 80% of the homes, the kitchen is separated from the rest of the rooms of the house. Kitchen ventilation is highly variable, depending on the building materials and design of the kitchen. Over 90% of kitchens have space between the wood panels of the walls and between the walls and roof where smoke can escape (Figure 3).

Most homes in Comachuén house several generations of the same family. For instance, one home could house the grandparents, their children and grandchildren. Therefore,

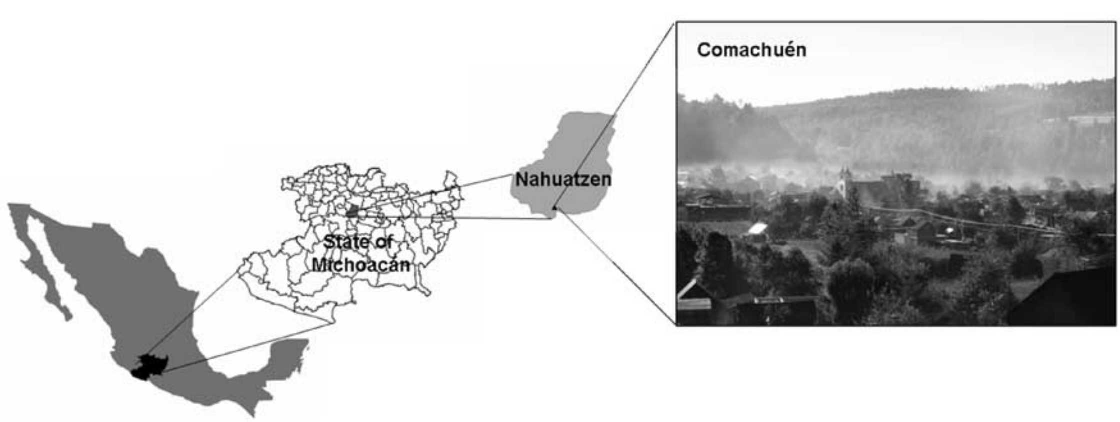

Figure 1. Town of Comachuén in the state of Michoacán.

Figure 2. View from the patio of a typical home of Comachuén.

Figure 3. Kitchen structure with ventilation between the walls and roof.

kitchens and stoves are often shared by several women, and in some occasions, multiple stoves are present in the same kitchen. In some homes, each woman has their own kitchen, leading to multikitchen homes. In Comachuén, nearly 60% of homes have two or more women who participate in cooking activities.

Sampling Plan

From November, 2004 to January, 2005, 53 homes using wood in open fires were visited in the community of Comachuén. Follow-up visits were made from April to May, 2005 in a subset of these homes after the installation of *Patsari* stoves. Both the initial and follow-up visits occurred during the dry season. The initial visits took place during the winter season, with average 24-h temperatures around 12°C (min: 3°C; max: 25°C), whereas the follow-up visits occurred

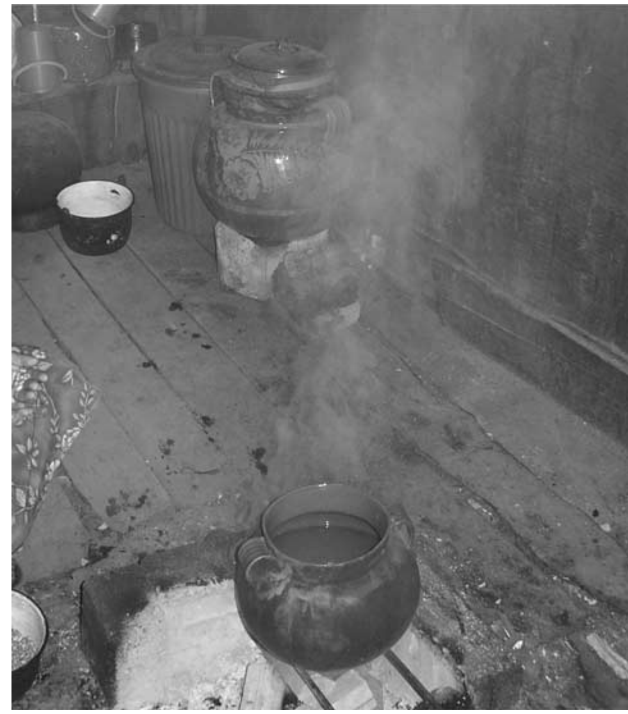

Figure 4. Open fire on the floor.

during the springtime, with average 24-h temperatures around 17°C (min: 8°C; max: 33°C). Participants were selected from the population of a larger health intervention study of 600 homes, restricted to families with children under 3 years of age and women of child-bearing age, that used wood in open fires for cooking (Figure 4). Additional criteria for inclusion in this study, beyond those used by the health intervention study, were that the kitchens had four walls and a roof. The *Patsari* stoves evaluated in the follow-up visits were donated to study participants (Figure 5).

Before initiating the study, a workshop was held to explain to the community the health impacts of wood smoke, the benefits of the *Patsari* stoves, and the objectives of the study. Field technicians visited the homes of potential participants, explained the objectives of the study, the benefits of the *Patsari* stoves and showed them the sampling equipment that would be placed in their homes. Once a volunteer showed interest in participating in the study, she was read an informed consent form, was asked to sign or mark it, and was left with a copy.

Sampling Methods and Microenvironments

Particulate matter with aerodynamic diameter of less than 2.5 μm ($PM_{2.5}$) concentrations were measured over a 48-h period to capture between day variability. Measurements were made in the following three microenvironments: (1) next to the stove (from here on "stove microenvironment"), monitors were placed 1 m horizontally from the stove's

Figure 5. *Patsari* stove.

combustion zone, at least 1.5 m from windows and doors, and 1.25 m above the ground; (2) in the kitchen away from the stove ("kitchen microenvironment"), monitors were located on average 1.4 m above the ground and 2.3 m from the stove; and (3) on the patio ("patio microenvironment"), with monitors placed 1.5 m above ground in a central location. The stove measurements were selected to identify the direct impact of open fires and Patsari stoves; the kitchen measurements were aimed to characterize exposures while women were in the kitchen, but away from the stove; and patio measurements intended to determine outdoor concentrations and exposures in an area of the home outside of the kitchen, where a considerable amount of household activity takes place. Additionally, $PM_{2.5}$ concentrations were measured in the central plaza of the community to characterize ambient concentrations.

SKC universal sampling pumps (model 224-PCXR8) were run intermittently (1 min on, 3 min off) at a flow of 4 l/min, with one-stage inertial impactors (SKC Personal Environmental Monitor, model 200) that capture particles on 37 mm Teflon filters (Gelman R2PJ037). Flow rates were measured before and after each sampling period using a calibrated rotameter. Volumes for sampling periods were calculated using the average between the pre-and post-flow rates. Samples in which the post-sampling flow rate or sample time deviated by more than 10% were not used. Filters were pre- and post-conditioned in a controlled environment (22°C$\pm$3°C and 40%$\pm$5% RH) and weighted with a microbalance (Cahn model C-35) at the National Center for Environmental Research and Training (CENICA) in Mexico City.

Quality Assurance

Approximately 15% (19 filters) of the total number of samples were collected as field blanks. Procedures for handling blanks were identical to those of exposed filters, only with no air drawn through their surface. Corrections to adjust for filter handling were made by adjusting the mass of sampled filters by the mean mass of the field blanks. Limits of detection (LODs) were estimated as three times the standard deviation of the field blanks divided by the 48-h nominal volume. The average LOD was found to be $2\,\mu g/m^3$. Approximately 10% (12 filters) of samples were duplicates, collocated next to another sampler for quality control. The mean percent difference between collocated samples was 16%.

Questionnaire and Time–Activity Logs

Questionnaires were applied to study participants during the monitoring period by trained field technicians from Mexico City to characterize house characteristics, fuel, and cooking patterns. Participants were asked about their cooking activities during the 2 days of monitoring (e.g. how many meals they cooked and for how many people, cooking duration, time spent near the stove, etc.), and about other potential sources of air pollution such as burning garbage on the patio or smoke entering their home from neighboring homes. In addition, information was obtained on exposure covariates such as fuel type, kitchen location, ventilation, stove location, number of women sharing the kitchen and stoves, etc. The follow-up questionnaire was modified to include questions concerning participant's use and maintenance of the *Patsari* stove. The questionnaires were tested in the communities before the study, and were adapted based on observations by field technicians. Time–activity logs were also applied to capture information about all of the participant's activities during the monitoring period, where these activities took place, and for how long. The questionnaires were used to validate time–activity logs in terms of cooking times and locations (where more than one kitchen existed).

Personal Exposure Estimation

To approximate participants' average daily $PM_{2.5}$ exposures during the monitoring period, we calculated time-weighted average concentrations, applying equation (1) (Özkaynak 1999) to the results obtained from the $PM_{2.5}$ measurements and time–activity logs.

$$\text{Total personal exposure} = \sum_{i=1}^{n} f_i * C_i \qquad (1)$$

where f_i is the fraction of time spent in microenvironment i and C_i is the 48-h $PM_{2.5}$ concentration in that microenvironment. We use this equation, ignoring the temporal variation of concentrations in each microenvironment, owing to the nature of our $PM_{2.5}$ sampling methods. We use stove measurements to characterize exposures during the time spent in the kitchen, because most of the time spent in the kitchen was near the stove and the location of the stove measurements were more standardized than the kitchen measurements. As $PM_{2.5}$ data was not collected in the bedrooms, we assume concentrations in the bedroom and other indoor environments to be the same as the concentrations on the patio. We use patio instead of kitchen concentrations, as the bedrooms and kitchens are separated by the patio in the majority of houses.

Results

Study Population

Of the 53 homes originally in the study, only 39 participants agreed to a follow-up visit and were found to be using their *Patsari* stoves regularly (at least once per day). This may not reflect stove adoption rates *per se* as some women were unavailable for a follow-up visit. Homes were visited 2–3 months after the installation of the *Patsari* stoves.

During the follow-up visit, 92% of homes still had an open fire, either in the kitchen where the *Patsari* stoves were built (42%), on the patio (18%), or in another room or kitchen of the house (32%). Not all of the open fires were necessarily used by the study participant, however, and 44% reported to only use their *Patsari* stoves during the follow-up visit. Approximately half (45%) of the study participants reported to cook with another woman, sharing their open fire or *Patsari* stove.

Microenvironmental Particulate Matter Concentrations

Baseline average concentrations in homes using open fires ranged from 94 $\mu g/m^3$ in the patio microenvironment to 693 $\mu g/m^3$ in the stove microenvironment. Intervention measurements, that is after *Patsari* stoves were installed, showed average levels ranging from 110 to 246 $\mu g/m^3$ in the patio and stove microenvironments, respectively (Table 1). Concentrations are reported at local temperature and pressure.

A clear reduction of $PM_{2.5}$ concentrations is observed in the stove and kitchen microenvironments after the installation of the *Patsari* stoves (Table 1, Figure 6), which were found to be statistically significant (Wilcoxon's test, $P<0.00001$ for stove measurement and $P<0.0001$ for kitchen measurement). In contrast, similar levels were found

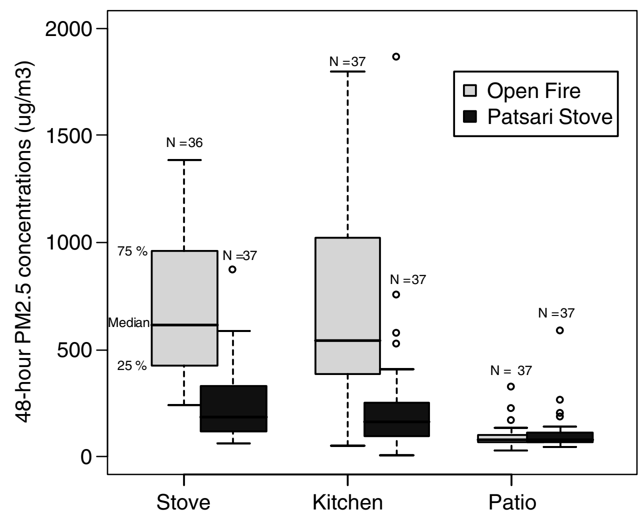

Figure 6. $PM_{2.5}$ concentrations in stove, kitchen, and patio microenvironments.

Table 1. Forty-eight hour $PM_{2.5}$ concentrations in stove, kitchen, patio, and community microenvironments

Microenvironment	N^a	Mean ($\mu g/m^3$)	SD	95% CI ($\mu g/m^3$)	Geometric mean ($\mu g/m^3$)	Median ($\mu g/m^3$)
Open fire measurements — baseline						
Stove	36	693	339	246–1338	615	616
Kitchen	37	658	434	67–1448	503	542
Patio	37	94	54	36–236	85	82
Main plaza (24-h)[b]	20	59	18	29–92	60	58
Patsari measurements — intervention						
Stove	37	246	175	63–614	197	188
Kitchen	37	255	312	59–864	180	187
Patio	37	110	92	51–295	94	82
Main plaza (48-h)[c]	12	61	8	49–75	60	60

[a]Not all microenvironments were monitored in all the homes during the baseline visits, therefore the sample size for each microenvironment does not equal 53.
[b]Measurements taken on the top of a 1 story building on the main plaza.
[c]Measurements taken on the top of a 2 story building on the main plaza.

in the patio before and after the *Patsari* stoves were installed (Wilcoxon's test, $P \approx 0.53$). Patio concentrations were significantly higher than those observed at the central plaza site (Wilcoxon's signed rank test, $P < 0.000001$). Emissions from the open fire and the *Patsari* stoves developed into homogeneous concentrations in the kitchen, as shown by the fact that levels in the stove and kitchen microenvironments were not significantly different from one another (Wilcoxon's test, baseline open fire $P \approx 0.737$, intervention *Patsari* stove $P \approx 0.316$).

Only paired measurements taken in the same homes before and after the intervention are presented in Table 2, to evaluate the actual reduction of particulate matter from the *Patsari* stoves.

Participants' Activity Information

During both the initial and follow-up visits, participants spent on average 19% of the day (4.7 h) in the kitchen, preparing and eating meals, 14% in the patio (3.3 h), washing dishes, sweeping, sewing, and relaxing, 54% in the bedroom (12.9 h), sleeping, relaxing, watching TV, and sewing, and 10% outside of the home (2.4 h), shopping, washing cloths, collecting water, etc. The rest of the time (3%) was spent in other rooms of the house or neighbor's homes.

Total Personal Exposure Estimates

We combined information on time spent in each microenvironment with their respective concentrations for each participant, to estimate the daily average personal $PM_{2.5}$ exposures of women in Comachuén. Applying equation (1), we found that the daily average personal $PM_{2.5}$ exposure for participants *before* the installation of the *Patsari* stove was 211 $\mu g/m^3$ ($n = 26$) and *after* the installation of the *Patsari* was 106 $\mu g/m^3$ ($n = 35$) (Figure 7), signifying an average reduction of 50%, which was found to be significantly different (Wilcoxon's test, $P < 0.000003$).

Each microenvironment contributed differently to participants' daily average exposure to $PM_{2.5}$, with time spent in the kitchen accounting for most of the exposure when using open fires during the baseline measurements. Once the *Patsari* stove was installed and kitchen concentrations decreased, time in the bedroom accounted for a higher fraction of the estimated personal exposure than the kitchen (Table 3).

Mixed vs. Exclusive use of the Patsari Stove

Although participants were encouraged to use their *Patsari* stoves as much as possible, only 17 of them (44%) reported that they exclusively used their *Patsari* stoves during the monitoring period. Sixty two percent of the women who used both the *Patsari* and open fire also shared their stoves with another woman of the house, which is nearly three times higher than those who exclusively used their *Patsari* stoves (Table 4). Although not captured in the questionnaire, the main reason given by participants as to why they continued to use their open fires was the additional time required to cook and heat water with the *Patsari* stove in comparison with the open fire. Furthermore, most participants continued to use the open fire for preparing nixtamal (82%) and heating bathing water (66%).

Although average $PM_{2.5}$ concentrations near the stoves were lower in "exclusive" *Patsari* homes (mean = 205 $\mu g/m^3$, SD = 120, $n = 16$) in comparison to "mixed" use homes (mean = 279 $\mu g/m^3$, SD = 210, $n = 20$), these differences were not found to be statistically significant (Mann–Whitney test, $P \approx 0.369$). The median $PM_{2.5}$ reduction for paired measurements found next to the stove in "mixed" use homes was 64%, whereas in "exclusive" *Patsari* homes was 72%.

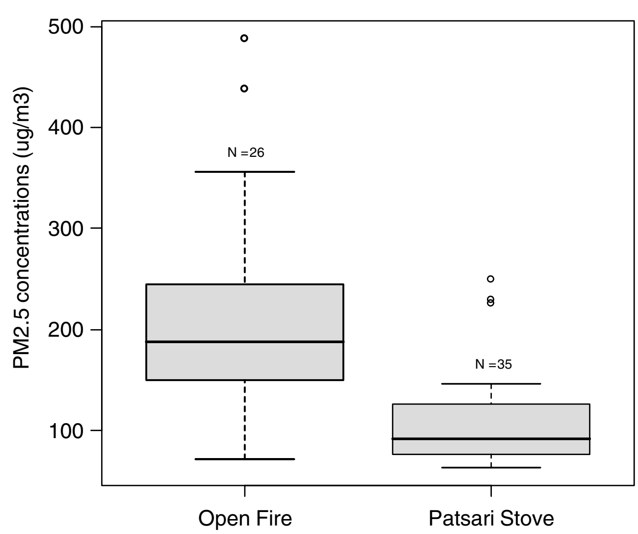

Figure 7. Estimated daily average personal exposures to $PM_{2.5}$ *before* and *after* the stove intervention.

Table 2. Paired differences in $PM_{2.5}$ concentrations for stove, kitchen, and patio microenvironments

Microenvironment	Median (%)	95% CI	Max (%)	Min (%)	N[a]
% Reduction stove concentrations	−71	−89–5	12	−90	27
% Reduction kitchen concentrations	−58	−90–56	72	−90	24
% Reduction patio concentrations	1	−48–259	372	−60	26

[a]N is not the same as the total number of participants in the intervention visits (39), since not all homes were measured in all three microenvironments for the baseline measurements.

Table 3. Average microenvironmental contributions to estimated total personal exposures

Microenvironment	Fraction of personal exposures associated with each microenvironment during baseline measurements (±SD)	Fraction of personal exposures associated with each microenvironment during intervention measurements (±SD)
Kitchen	61% (±18%)	35% (±18%)
Patio	7% (±6%)	11% (±8%)
Bedroom	25% (±11%)	47% (±15%)
Other indoor	2% (±4%)	1% (±4%)
Community	5% (±11%)	6% (±6%)

Table 4. Questionnaire results for "exclusive" and "mixed" use of the *Patsari* stove

	Exclusive *Patsari* use ($n=17$)	Mixed *Patsari*/open fire use ($n=21$)
Open fire in the kitchen	35% (six homes)	48% (10 homes)
Open fire elsewhere in the home	47% (eight homes)	57% (12 homes)[a]
Average number of people eating in the house	6 (2–10)	7 (3–15)
Share Patsari stove with another woman of the house	23% (four homes)	62% (13 homes)
Claim that the Patsari is difficult to light	6% (one homes)	33% (seven homes)
Use the Patsari to make nixtamal	41% (seven homes)	0%
Use the Patsari to heat bathing water	53% (nine homes)	19% (four homes)

[a]One home had open fires in both the kitchen and patio.

Discussion

We found that kitchen $PM_{2.5}$ levels in homes burning wood in open fires were over 10 times higher than Mexican outdoor 24-h $PM_{2.5}$ standards set at $65\,\mu g/m^3$ (SSA 2005). Kitchen levels were higher than in other Mexican studies (Brauer et al., 1996; Saatkamp et al., 2000; Riojas-Rodriguez et al., 2001), while falling within the range of comparable studies worldwide (Saksena et al., 2003). The range of concentrations found in the kitchen microenvironment was larger than next to the stove, owing to differences in ventilation and the location of the kitchen microenvironment monitors, which depended on the layout of each kitchen. Ambient outdoor concentrations were elevated in Comachuén as well, exceeding Mexican standards a third of the days monitored.

The installation of the *Patsari* stoves resulted in a median 71% reduction in 48-h $PM_{2.5}$ concentrations near the stove and 58% reduction in the kitchen; however, indoor concentrations remained nearly four times higher than outdoor standards. Several studies that have been conducted in Guatemala to evaluate the impacts of the *plancha* stove on indoor air pollution (Naeher et al., 2000; Albalak et al., 2001; Bruce et al., 2004) found comparable results. These studies, however, were longitudinal in design, and therefore the changes in concentrations found could be influenced by household factors (such as household size, income, design, etc.) and not necessarily to the use of the improved stoves. This study differs in that we tried to reduce the influence of household factors by measuring $PM_{2.5}$ levels before and after the installation of improved stoves in the same homes, although concentration levels could still be affected by differences in activity patterns between the before and after measurements.

No significant impact on patio concentrations was found with the introduction of the *Patsari* stoves, perhaps owing to the influence of neighboring homes and kitchens, emissions coming from the chimney of the *Patsari* stoves or open fires located on the patio. Although much of the reduction in emissions from the *Patsari* stoves occurs because of the improved combustion chambers, a larger study would be needed to determine if the use of chimneys results in increased outdoor air pollution levels. The size and design of this study does not permit us to draw such conclusions, however.

Although the initial visits took place during the winter while the follow-up visits occurred in the spring, both measurement campaigns occurred during the dry season. Average temperatures during the follow-up visits were approximately 5°C higher than during the initial visits; however, ventilation levels in the homes were found to be essentially the same. Participants also reported similar activities in terms of the number of meals they prepared and people eating in their households as well as the amount of time spent outdoors. We assume, therefore, that although the visits occurred during different seasons, this did not have a significant affect on activity patterns or pollution levels.

Estimated daily average personal exposures to $PM_{2.5}$ were $211\,\mu g/m^3$ with the use of open fires, which is similar to estimates for southern India of $231\,\mu g/m^3$ (Balakrishnan

et al., 2002). The installation of the stoves led to 50% reductions of estimated daily average personal exposures. The majority of exposures to $PM_{2.5}$ originated from time spent in the kitchen during the baseline measurements. Once the *Patsari* stoves were installed, this contribution reduced to less than half of the total exposure, with a concurrent rise in contributions by the other microenvironments. As mentioned previously, temporal variability was not considered, which has been found in other studies to have a significant impact on total personal exposures, with peak emissions episodes contributing to between 31% and 61% of total personal exposures (Ezzati et al., 2000b). The fact that we used 48-h average concentrations may therefore result in underestimates of daily average personal exposures, the contribution of the kitchen microenvironment, and the reductions owing to the improved stoves. Furthermore, while the use of 48-h measurements may smooth over some of the between-day variability, perhaps it does not capture it all, which could lead to greater uncertainty in the results.

We were unable to gather information on bedroom concentrations in this study, as the noise created by the pumps is a significant burden on participants, and therefore we approximated exposures in the bedroom as equivalent to patio levels. As described above, typical home structures (80% of homes) have the kitchen physically separated from the bedrooms, often by a patio. In addition, only four homes reported other sources of pollutants in the bedrooms (such as candles or smoking), leading us to assume that $PM_{2.5}$ levels in the bedroom are most similar to patio levels. During the initial visits, 12-h measurements of $PM_{2.5}$ were taken in the bedrooms of several homes, and average daytime levels of $PM_{2.5}$ were found to be on the order of approximately 150 $\mu g/m^3$ ($n = 28$). Although higher than patio levels, this average only represents daytime levels, and it can be assumed that if taken over the full 48-h period, $PM_{2.5}$ concentrations in the bedroom would be even lower, and thus closer to patio levels than kitchen concentrations. Bedroom concentrations could be either higher or lower than outdoor levels, however, depending on the location and ventilation of the bedrooms and at least seven of the homes had bedrooms attached to the kitchens, which could result in higher bedroom $PM_{2.5}$ levels. Given that over half of participants' time was spent in the bedroom, exposure misclassification could result from applying equation (1) to these situations in rural Mexico, and future measurements in this microenvironment are needed.

Another source of uncertainty in the estimation of personal exposures is the quality of responses obtained from the questionnaires and time–activity logs. Although field technicians were trained in the local community, and came to have a good understanding of the time–activity patterns of the study participants, it was clear that many of the participants did not have a very accurate sense of time. The uncertainty in the time–activity data, therefore, could lead to significant error in the calculations of personal exposures and in determining the contribution of different microenvironments to total personal exposures. Further work is needed to adequately characterize time–activity patterns in rural environments.

Since follow-up visits took place 2–3 months after the installation of the *Patsari* stoves, while some of the participants were still transitioning to the new stove technology, the observed reductions may well change over time. Adaptation to improved *Patsari* stoves can mean a significant behavioral change for many women, as it often includes shifting from cooking on the floor in a kneeling position to the standing position, chopping wood into smaller pieces, longer cooking times, and technology that requires frequent maintenance for adequate performance. The impact of the stoves on indoor air quality may improve with time, as participants use their stoves more, or deteriorate as participants abandon the new technology or fail to provide proper maintenance or use, as has been observed with other stove dissemination efforts (Bruce et al., 2004). It is important, therefore, that longer term impacts of improved stove programs are also evaluated.

Nearly all homes still had open fires during the follow-up visit, used by the study participants or other members of the home. The majority of the participants continued to use their open fires for heating bathing water and preparing nixtamal. Anecdotal evidence from households suggests that pots with bathing water or nixtamal may be heavy to lift up onto the *Patsari* stoves and that heating times for large volumes of liquid may be faster with open fires. Although these activities do not occur on a daily basis, they occur every few days, which has implications for the timing and length of monitoring periods, and epidemiological associations. Stove designs should take these activities into consideration. Furthermore, many homes have multiple families and women cooking in separate or shared stoves and kitchens, which should be taken into consideration for both the stove and study design. Here, we find that women who share their stoves and kitchens are more likely to continue using the open fire in their home, possibly as a result of needing additional cooking space. Another factor that could have had an impact on stove adoption levels is the fact that the stoves in this study were donated to the participants, which could affect participants' attitudes and the value they place on the stoves. Further research should be conducted to determine the implications of the stove donations on its acceptance and use rates.

Even though not all participants in the study made a full transition to their *Patsari* stoves at the time of the follow-up visit, kitchen $PM_{2.5}$ levels in homes that continued to use an open fire were still reduced by over 60%. The difference between stove and kitchen $PM_{2.5}$ levels in "mixed" use homes and "exclusive" *Patsari* homes was not found to be statistically significant; however, this may be related to the sample size or the reliability of questionnaire responses.

This study documents the reductions of indoor air pollution from improved wood-burning stove programs by comparing levels before and after the installation of *Patsari* stoves in rural Mexican homes. We show that the *Patsari* stove can result in large reductions of home $PM_{2.5}$ levels and daily average personal exposures, therefore contributing to cleaner and healthier environments. Both indoor levels and personal exposures are still higher than outdoor air quality standards. Further research is needed on stove use patterns and home energy preferences to determine the sustainability of the environmental benefits of the *Patsari* stoves.

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